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Barthe et al.

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(54) **APPARATUS FOR THREE DIMENSIONAL
ULTRASOUND IMAGING**

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(73) Assignee: **Guided Therapy Systems, Inc.**, Mesa, AZ (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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This patent is subject to a terminal disclaimer.

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Related U.S. Application Data

(63) Continuation of application No. 09/113,227, filed on Jul. 10, 1998, now Pat. No. 6,036,646.

(51) **Int. Cl.**⁷ **A61B 8/12**

(52) **U.S. Cl.** **600/445**

(58) **Field of Search** 600/459, 443, 600/439, 446, 463; 606/159; 310/334; 128/916

(57) **ABSTRACT**

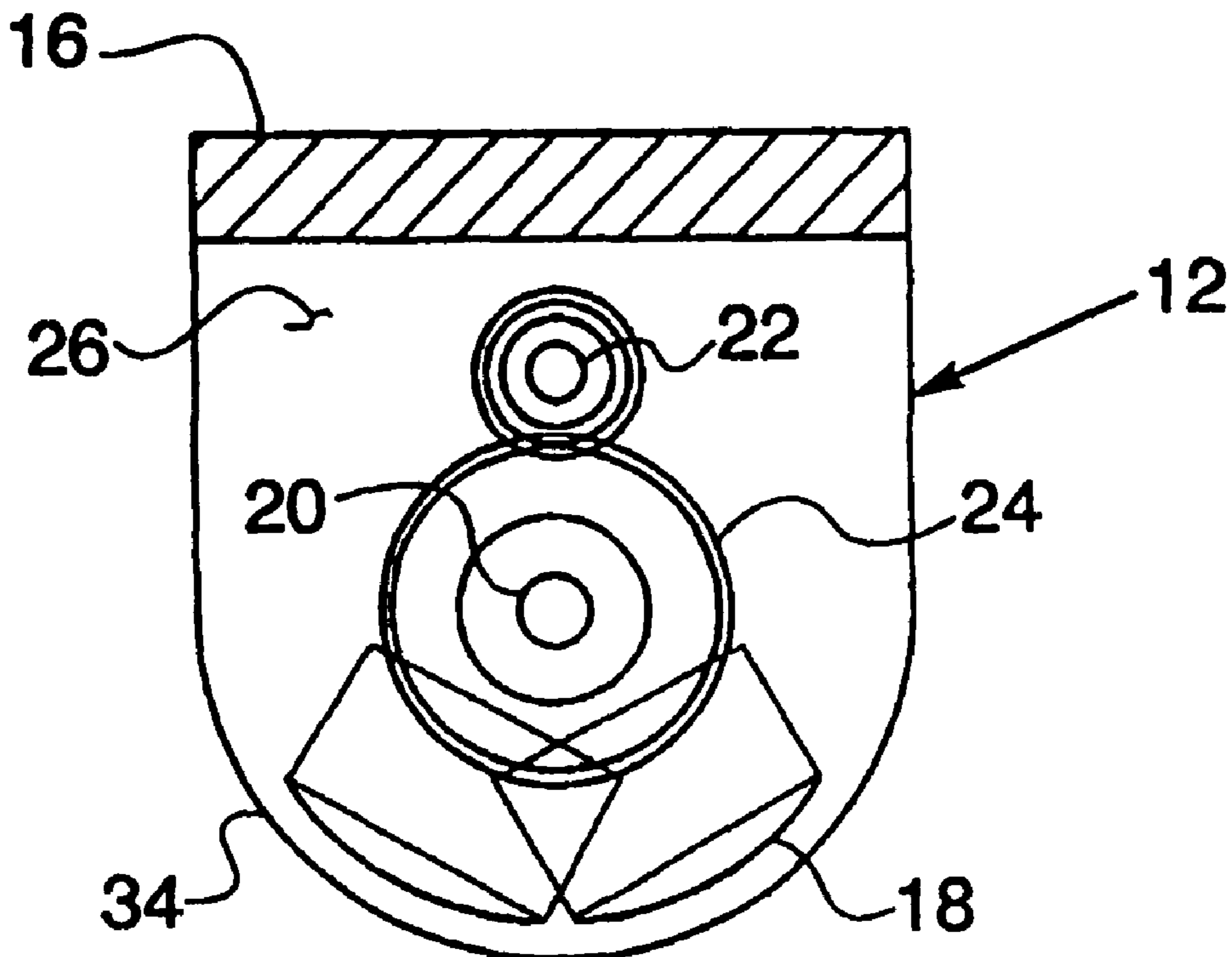
A method and apparatus for medical diagnostic ultrasound imaging that utilizes a one, one and one-half or two dimensional scanhead for performing three dimensional imaging. The method and apparatus limits acoustic reverberations by swinging or rotating an array of ultrasound transducer elements about the longitudinal axis of the probe of an ultrasound transducer apparatus to enable the transducers to maintain a constant and concentric position with the acoustic membrane of the probe.

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9 Claims, 3 Drawing Sheets



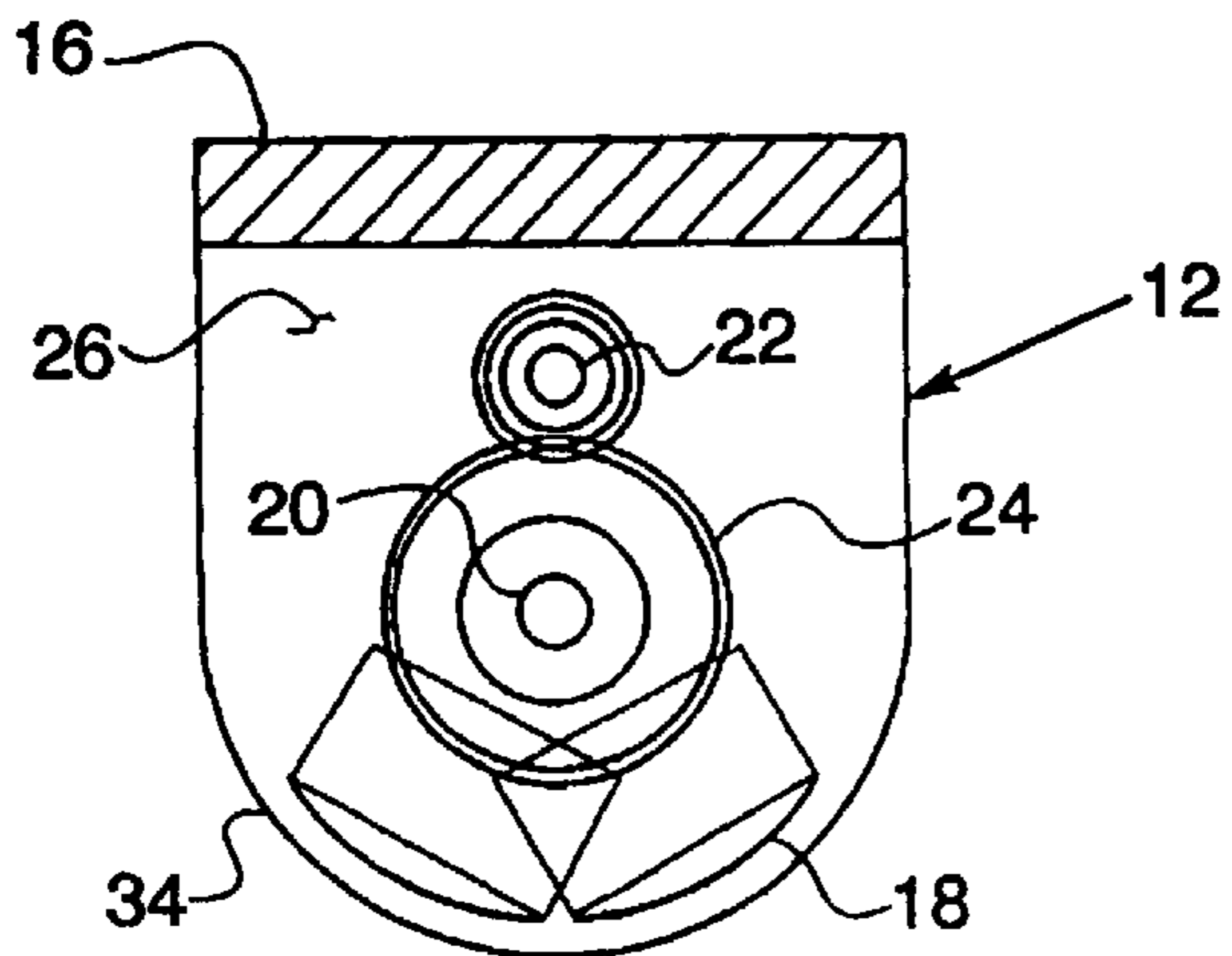


FIG. 1.

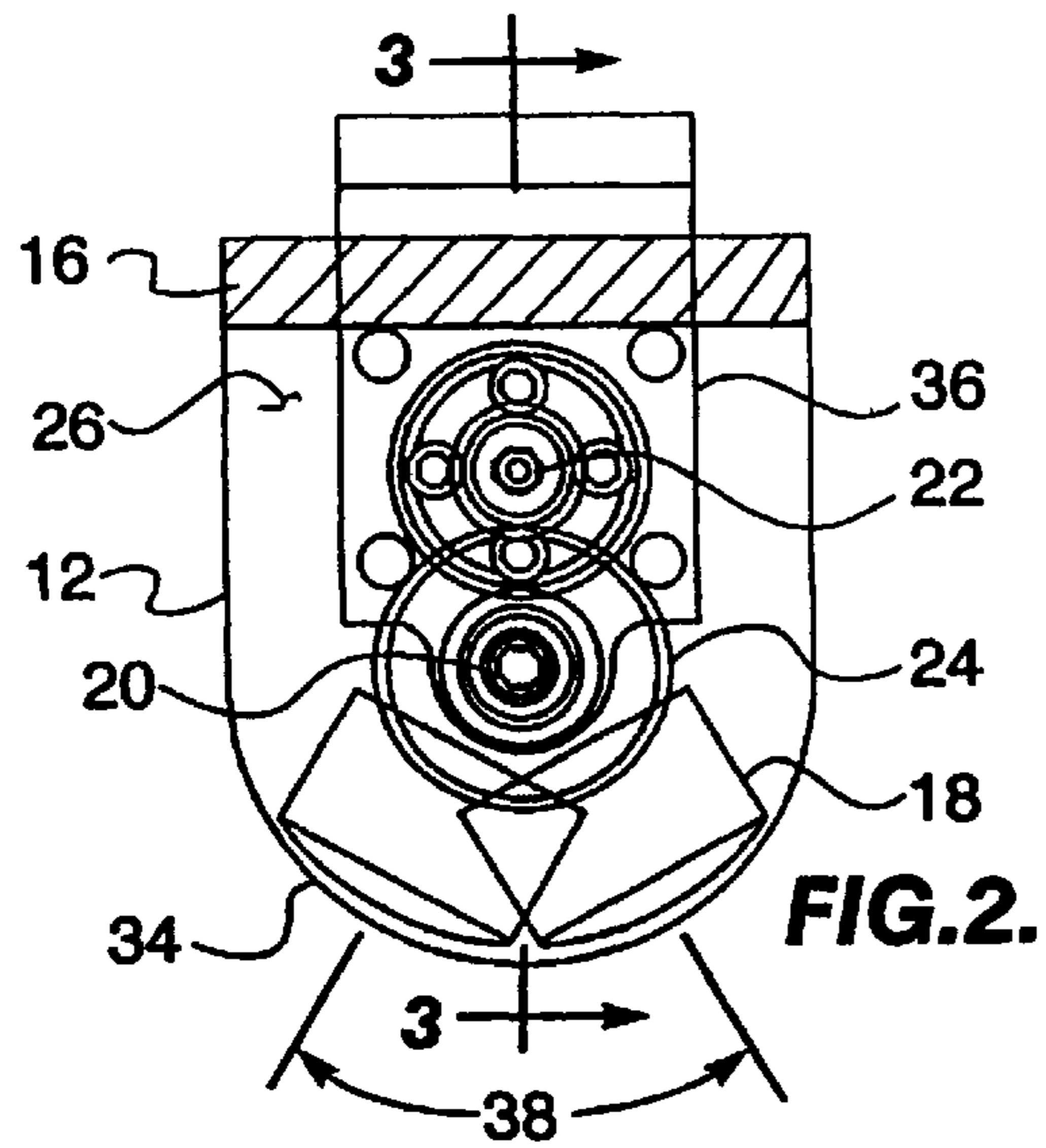


FIG. 2.

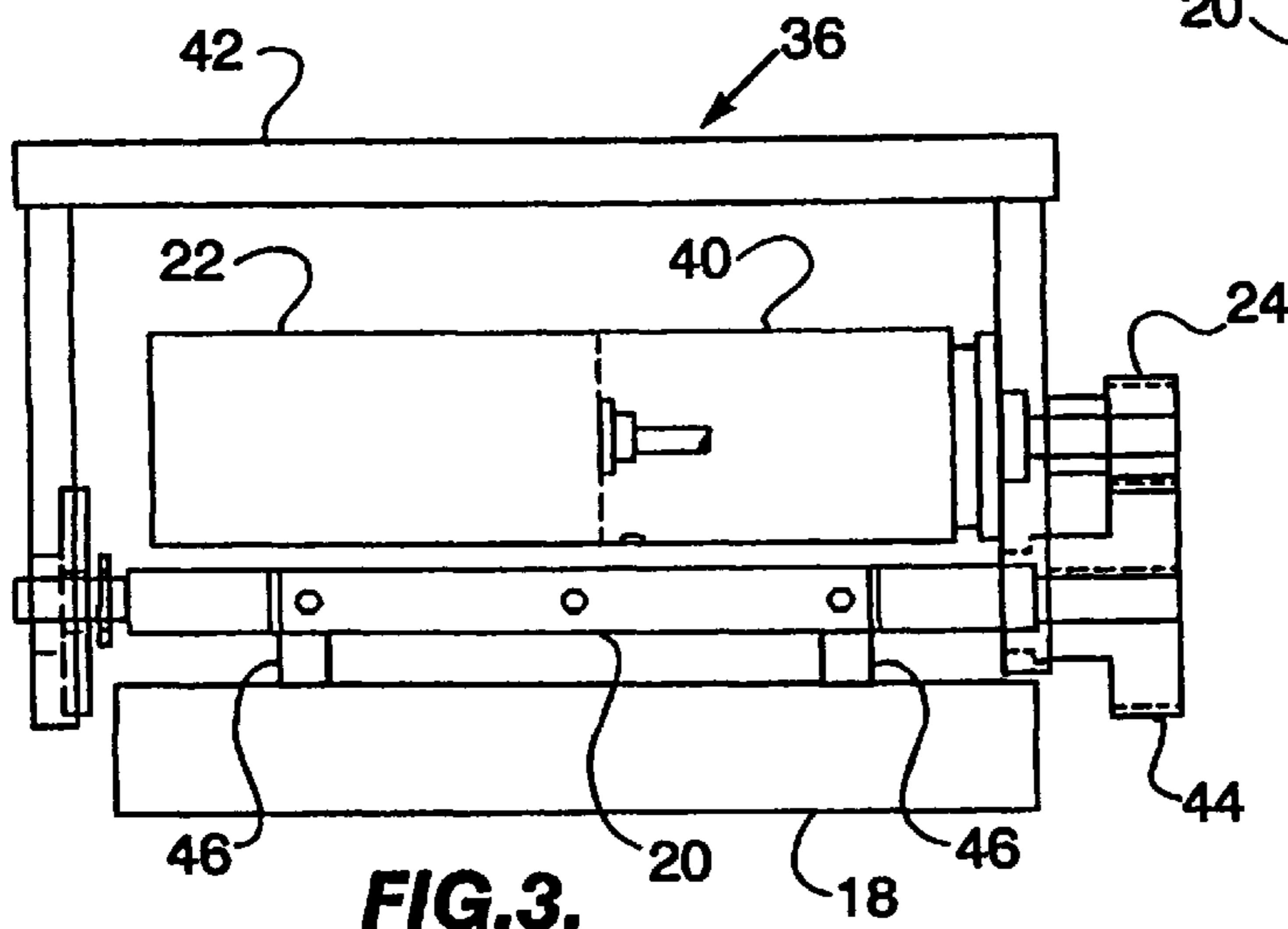


FIG. 3.

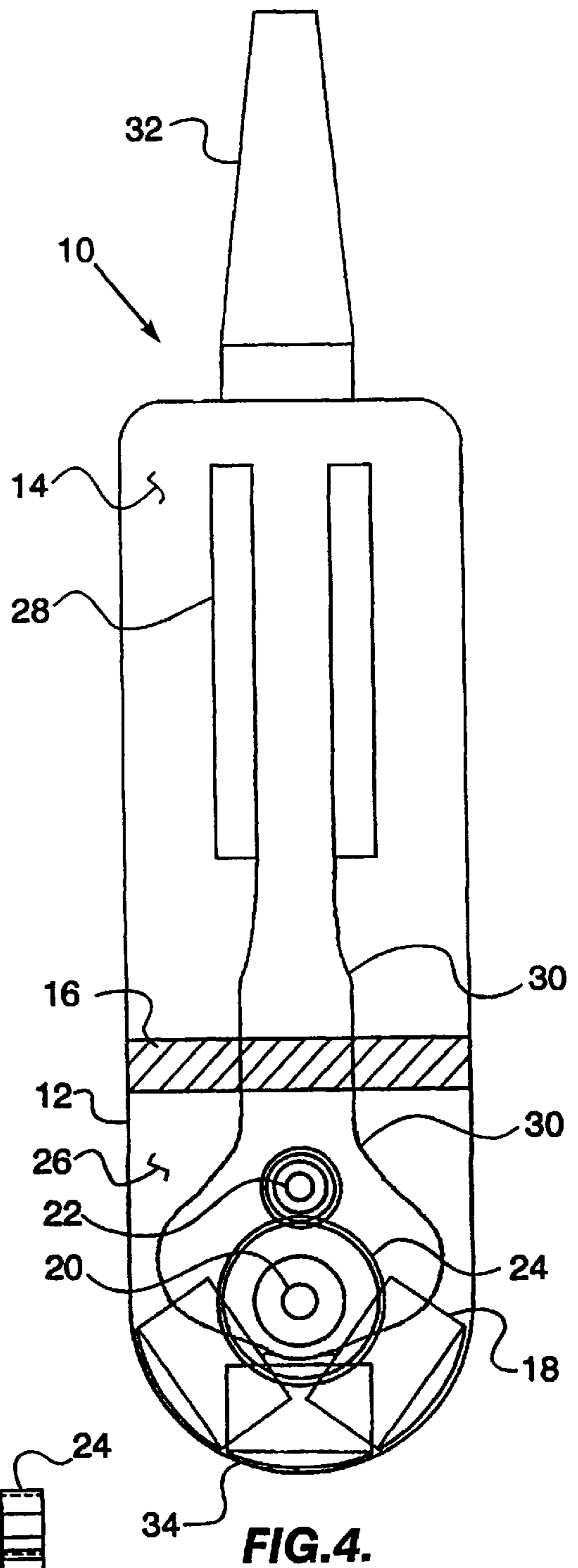
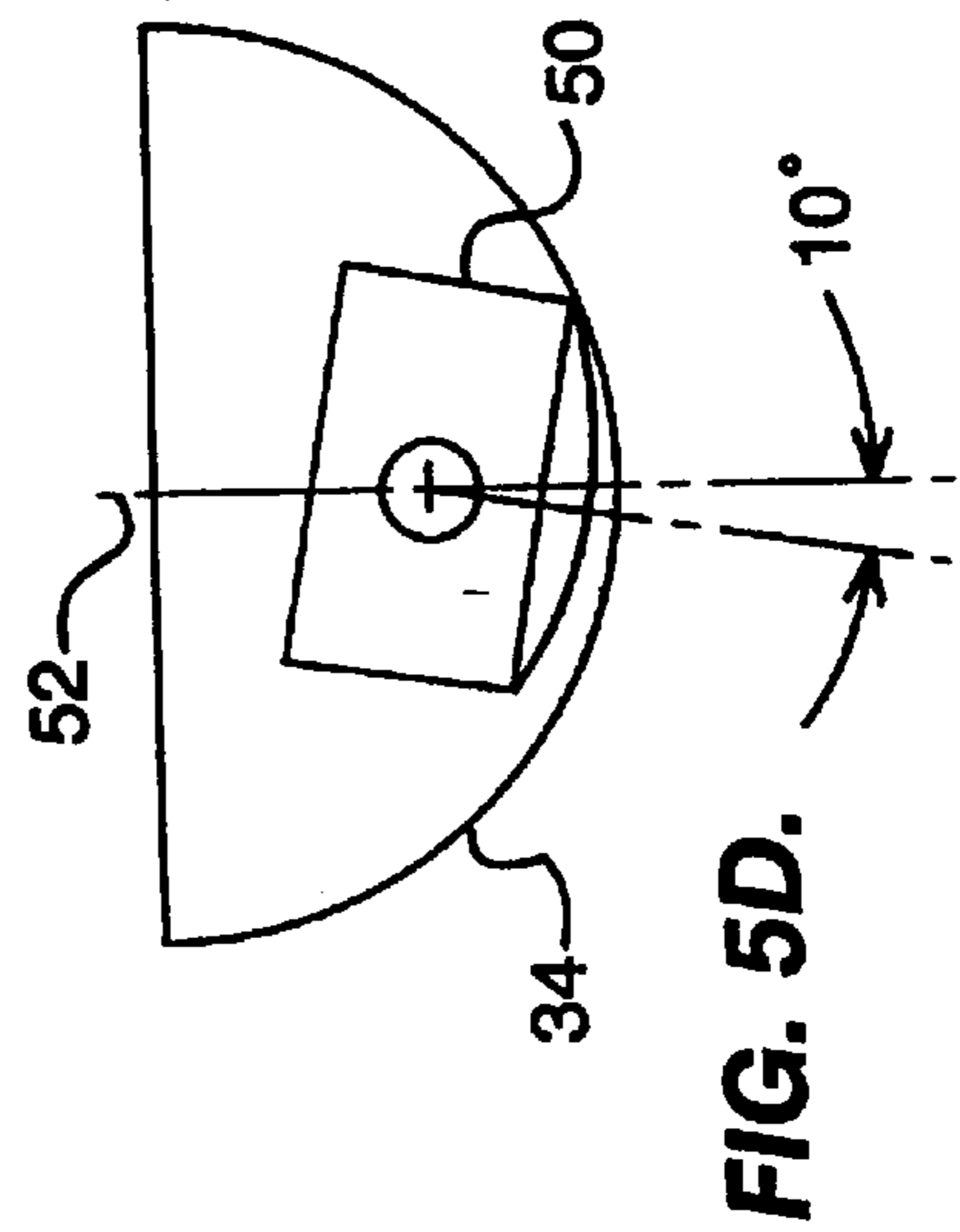
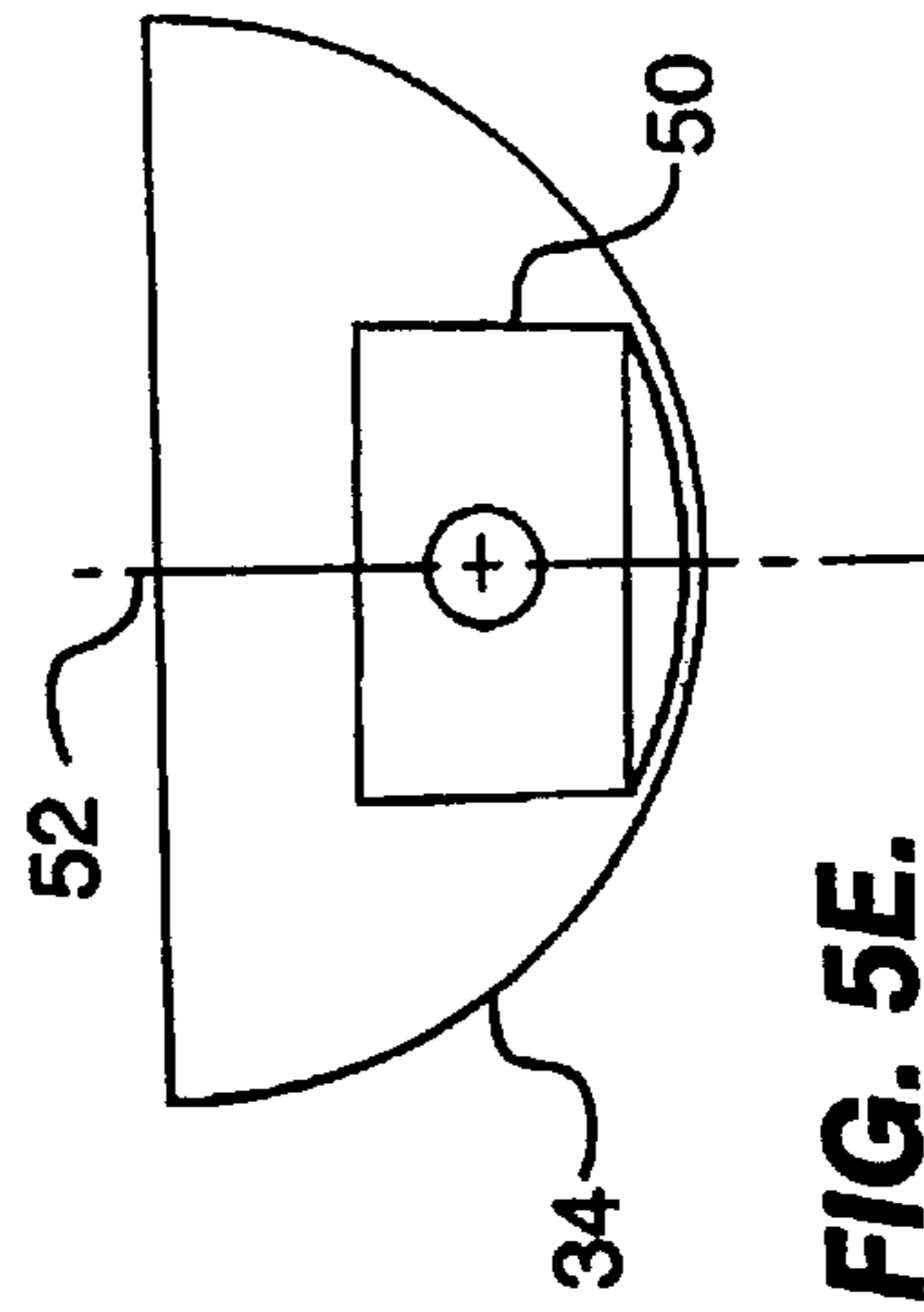
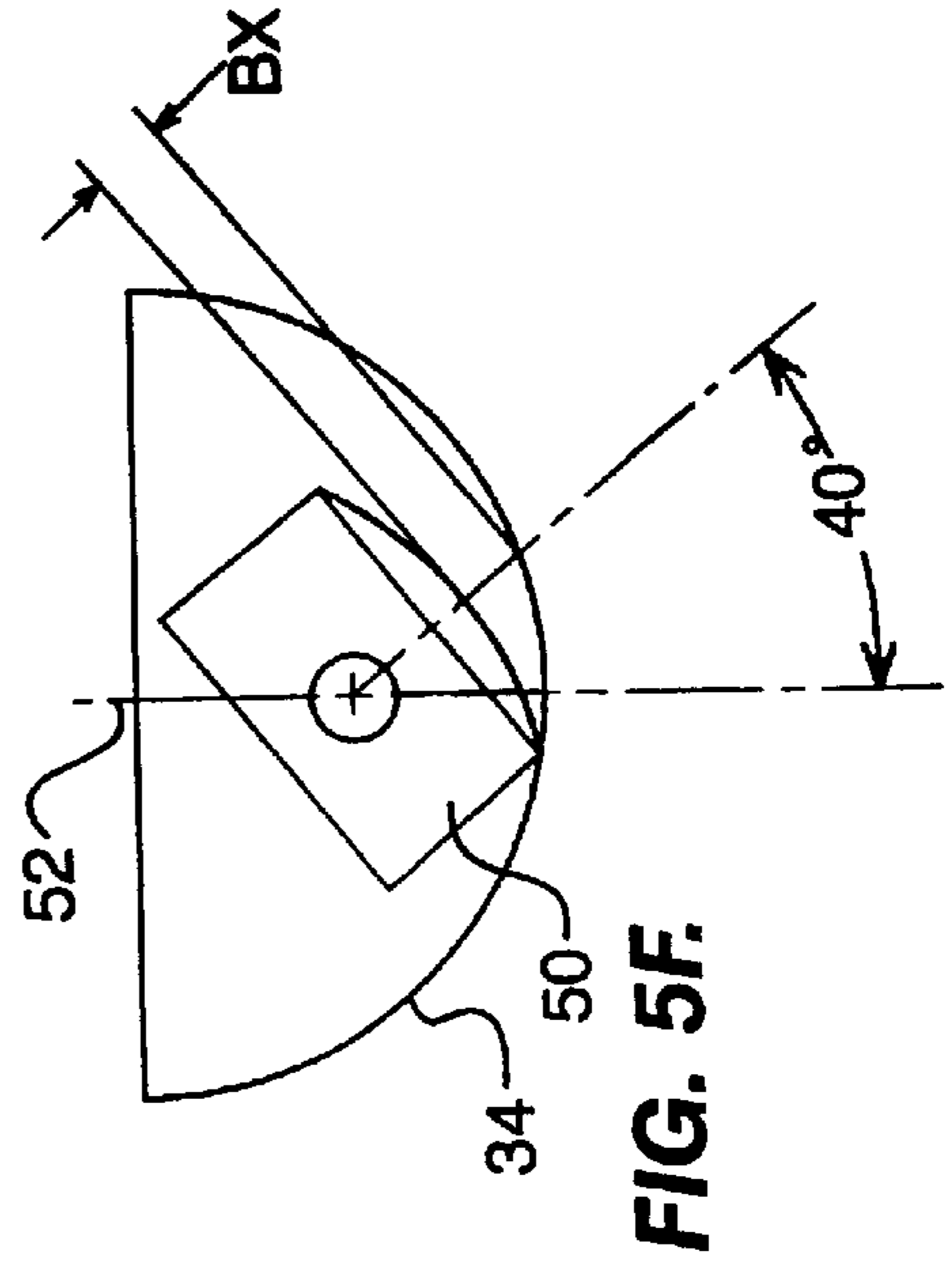
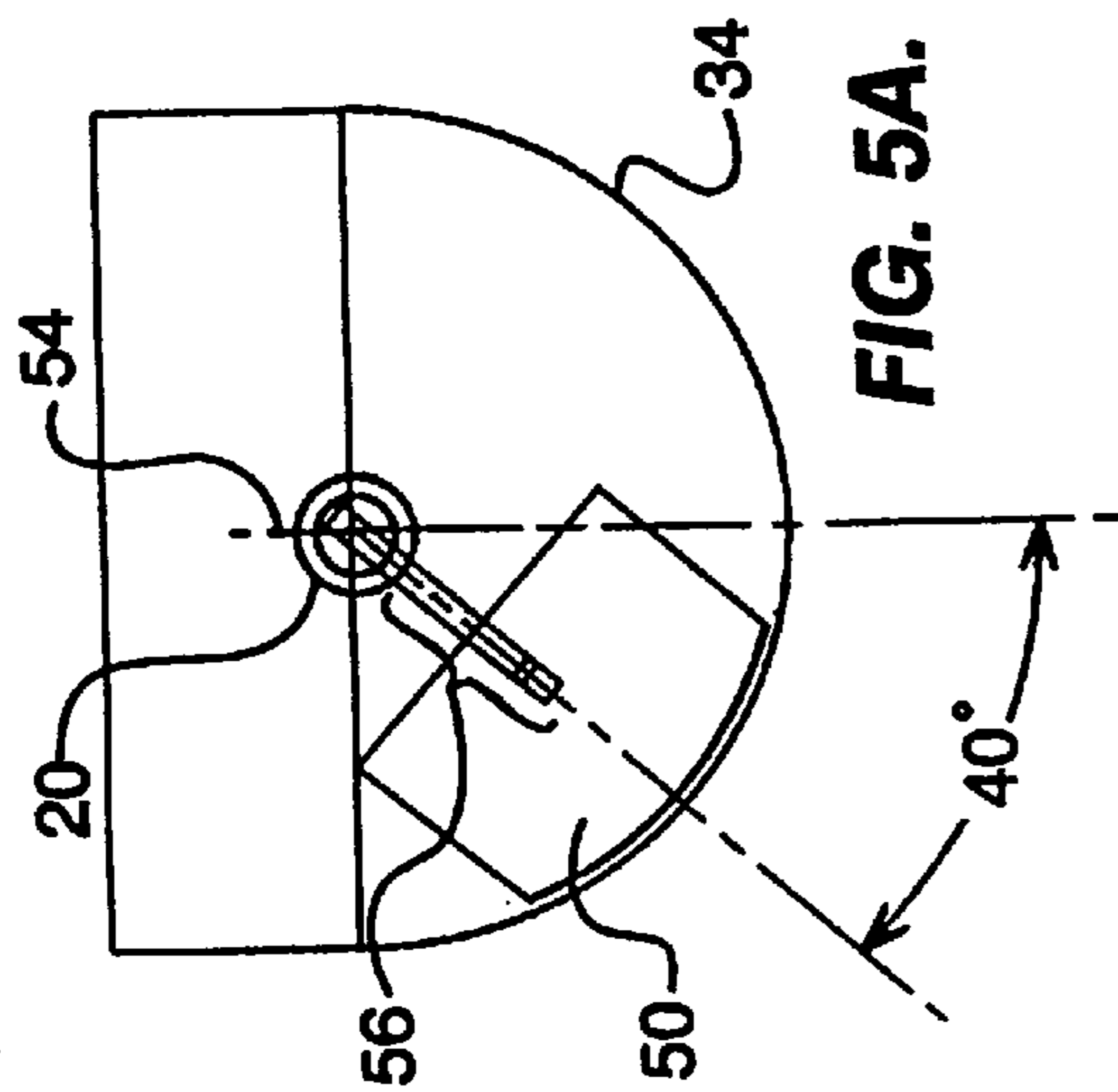
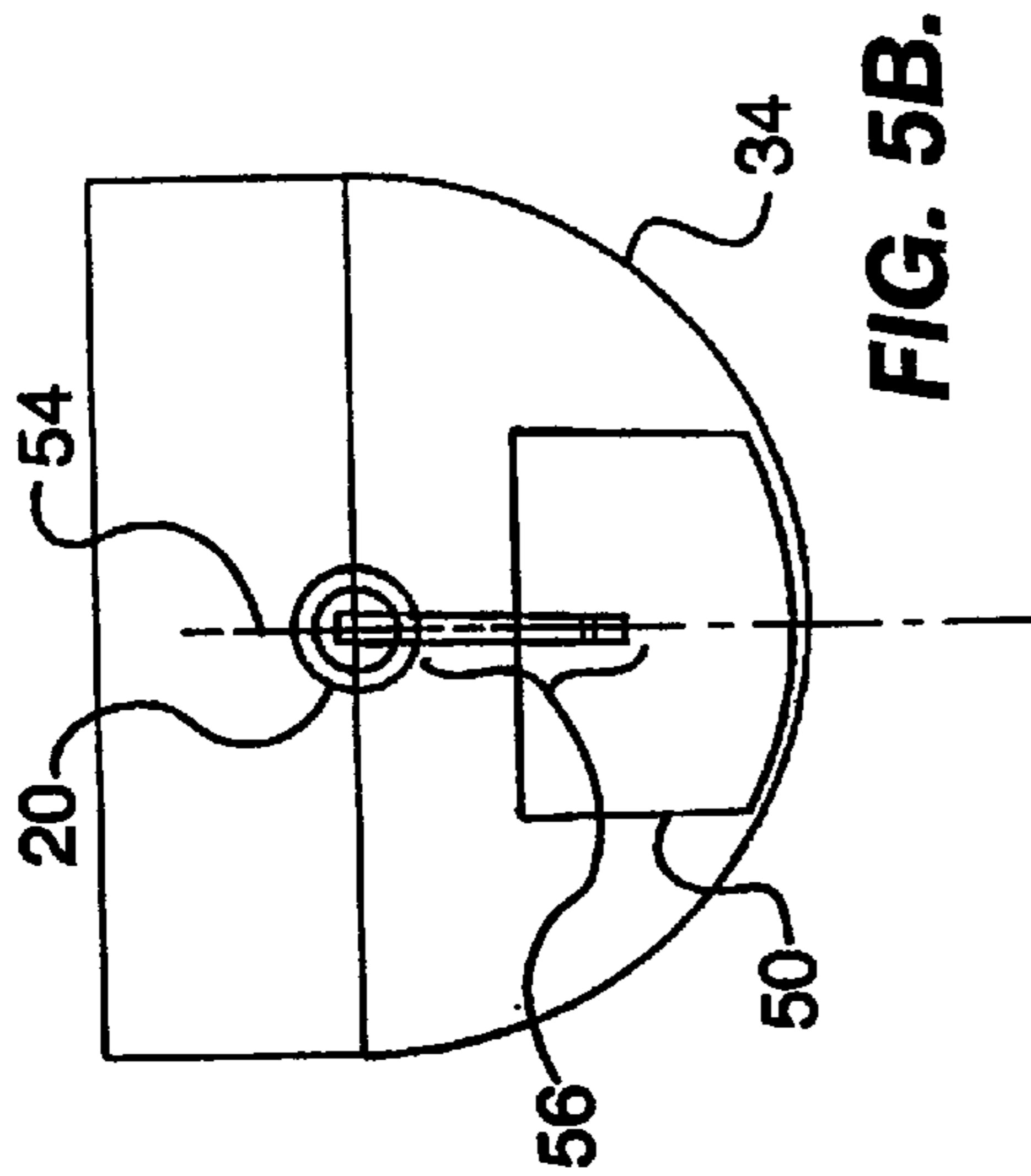
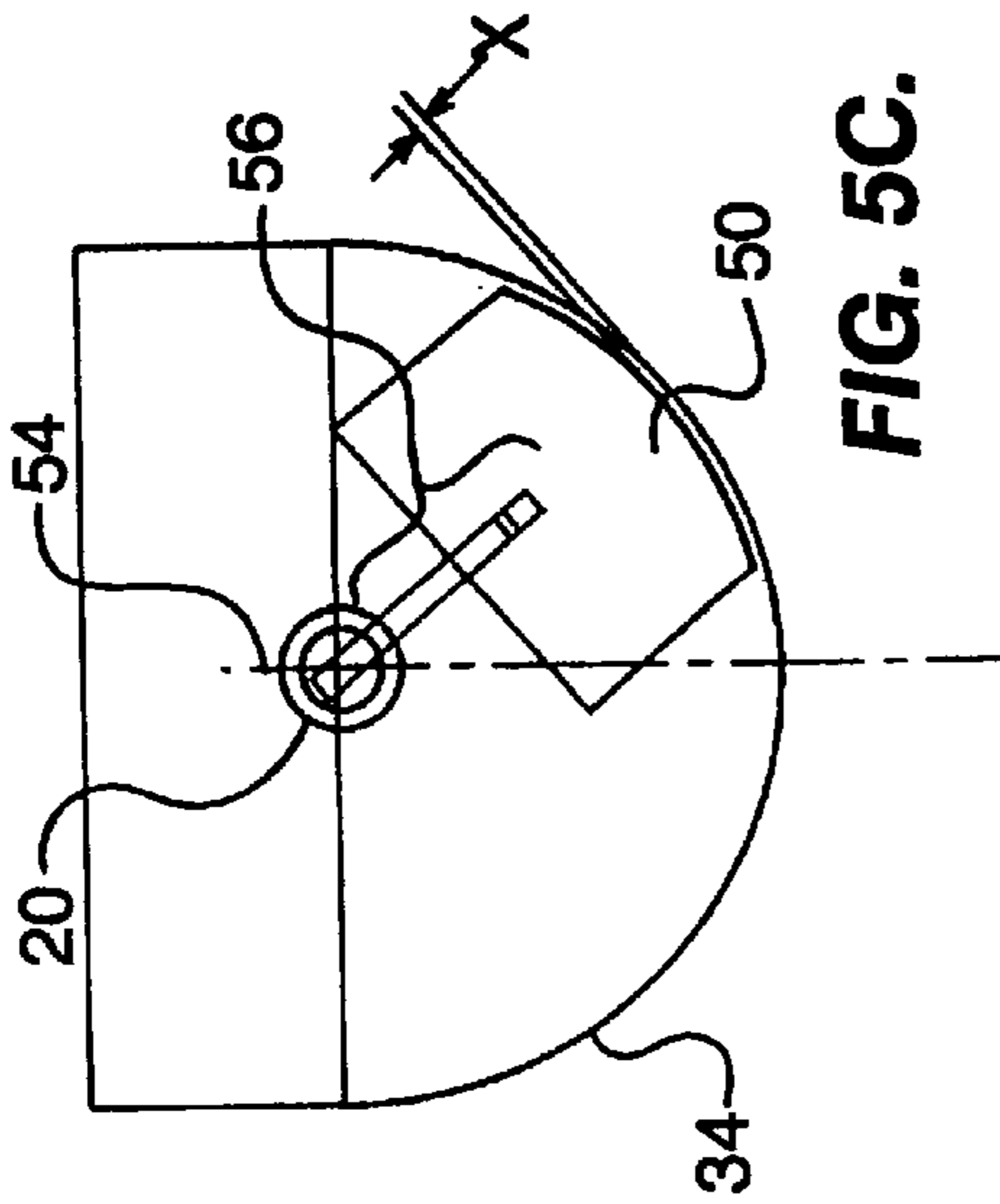


FIG. 4.



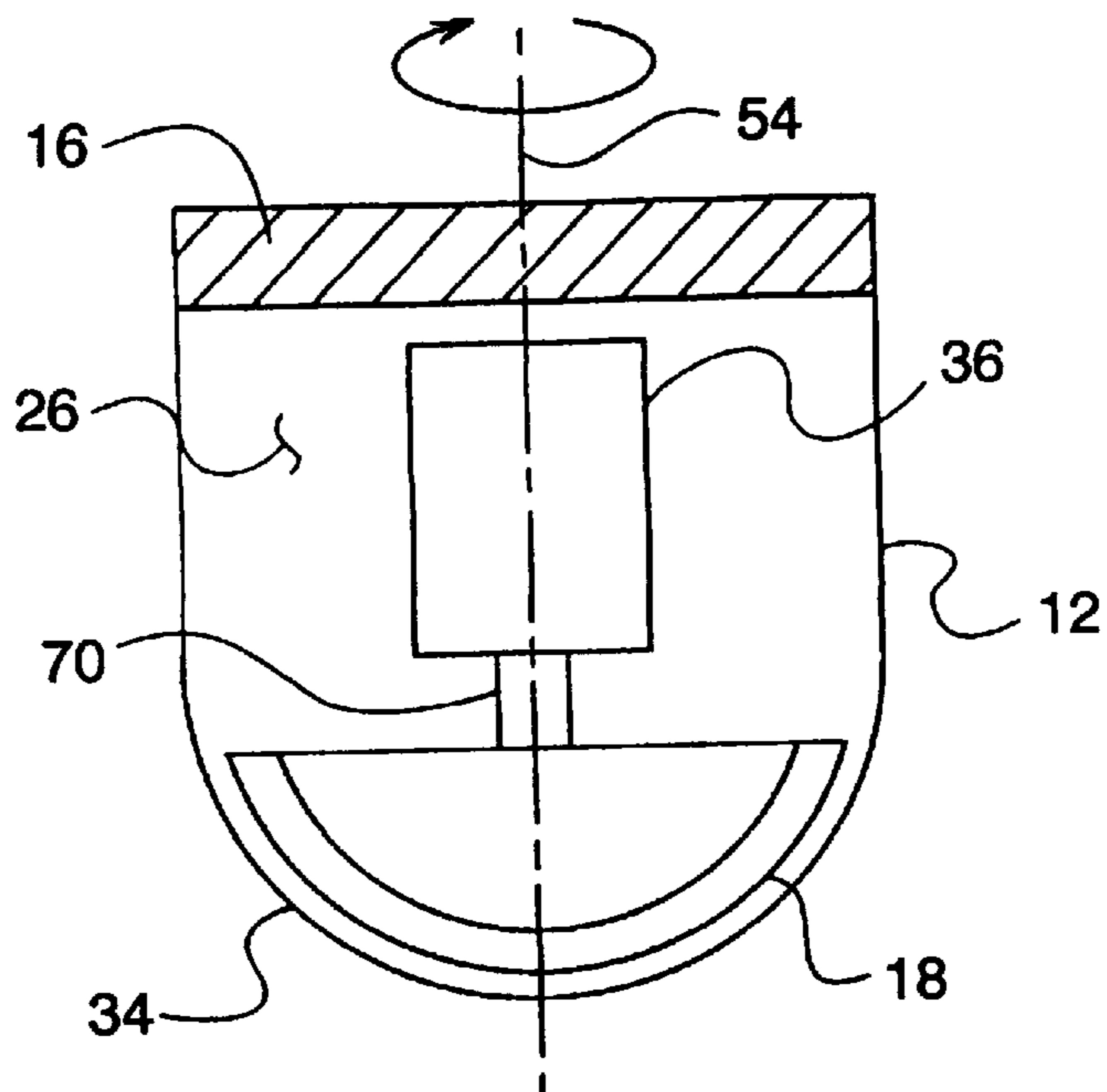


FIG. 6.

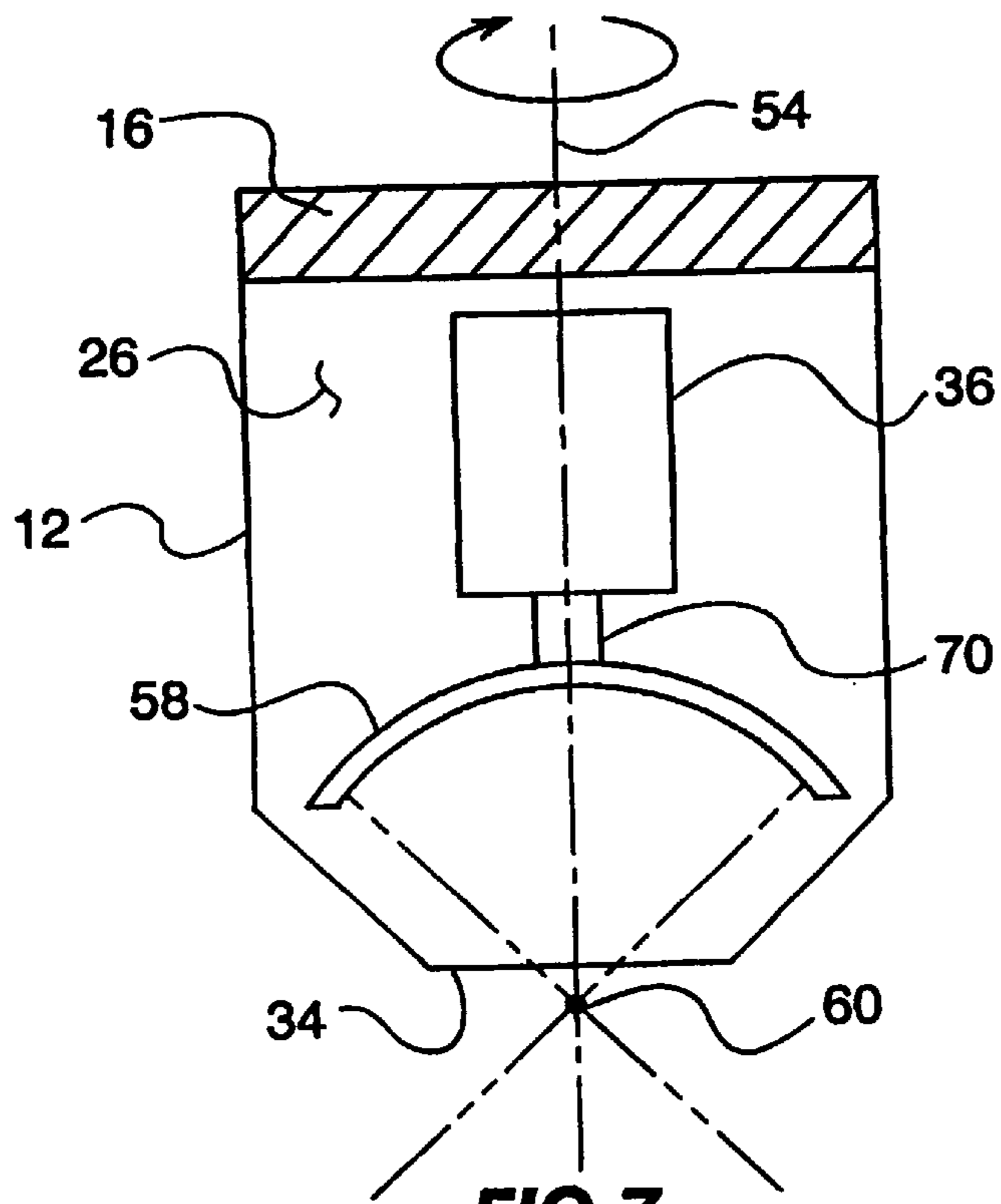


FIG. 7.

APPARATUS FOR THREE DIMENSIONAL ULTRASOUND IMAGING

REFERENCE TO RELATED DOCUMENTS

This application is a continuation application of U.S. patent application Ser. No. 09/113,227, filed Jul. 10, 1998 now U.S. Pat. No. 6,036,646, and entitled "METHOD AND APPARATUS FOR THREE DIMENSIONAL ULTRASOUND IMAGING".

FIELD OF THE INVENTION

The present invention generally relates to a method and apparatus for ultrasound imaging for medical diagnostic procedures that utilizes a one, one and one-half, or two dimensional scanhead for performing three dimensional imaging. More particularly, the present invention is directed to a method and apparatus for diagnostic ultrasound imaging which includes the act of swinging or rotating an array of ultrasound transducer elements about the longitudinal axis of a shaft, at a predetermined distance from the shaft, to enable the transducers to maintain a constant distance from the membrane throughout the swing or rotation of the transducers. This method of ultrasound imaging limits acoustic reverberations during imaging thereby decreasing unusable images.

BACKGROUND OF THE INVENTION

The rotating of ultrasound transducer arrays contained in ultrasound imaging apparatus in order to produce three-dimensional images is common in the prior art. For example, U.S. Pat. No. 5,662,116 issued to Kondo et al. discloses a multi-plane electronic scan ultrasound probe having a rotary member mounted on the distal end of an elongated catheter and an ultrasound transducer, namely a large number of ultrasound elements positioned in a row, mounted on the rotary member. The ultrasound probe has a tilting mechanism to tilt the rotary member which in turn tilts the ultrasound transducer.

Another patent, U.S. Pat. No. 5,159,931 issued to Pinni describes an apparatus which achieves the three-dimensional reconstruction of anatomic structures by acquiring two-dimensional echographic images produced by real time processing of signals that are reflected and/or scattered by the structures when they are hit by an ultrasound beam generated by a piezoelectric transducer contained within an echographic probe. In use, the sector scan transducer rotates through a 180 degree angle around the longitudinal axis of the probe.

Another example of a rotating ultrasound transducer array used in an ultrasound imaging apparatus to create a three-dimensional image can be seen in U.S. Pat. No. 5,070,879 issued to Herres. The Herres patent discloses an ultrasound imaging apparatus having a probe disposed on a longitudinal axis and ultrasound transducer elements arranged along the axis of the probe. The ultrasound array alternates between remaining stationary and oscillating about the axis of the probe in order to define a sector. In the first mode, where the array is held stationary, the transducer elements are operated successively to generate a longitudinal rectilinear scan. In the second mode, where the array is oscillated, the transducer elements are repeatedly operated to generate a transverse sector scan orthogonal to the longitudinal scan. The transducer elements are operated in one mode repeatedly at all of the transducer element positions of the other mode to generate a three-dimensional scan.

Although the generation of three-dimensional images using ultrasound imaging apparatus which contain ultrasound arrays that are rotated about a center axis is common in the field of art, there is a need for an improved ultrasound imaging apparatus for three dimensional ultrasound imaging which utilizes an ultrasound imaging apparatus that utilizes an array which can focus in the elevation dimension and that comprises a structural make-up which limits maintenance and failure of the apparatus

SUMMARY OF THE INVENTION

It is a principal object of the present invention to provide a method and apparatus for performing three-dimensional ultrasound imaging for diagnostic procedures that utilizes a scanhead having a one, one and one-half dimensional, or two-dimensional array of ultrasound transducer elements.

It is another object of the present invention to provide a method and apparatus for performing ultrasound imaging for diagnostic procedures that utilizes an array that can focus in the elevation dimension in order to provide more flexibility and better shape of the focal region.

It is still another object of the present invention to provide a method and apparatus for performing three-dimensional ultrasound imaging having an array of ultrasound transducer elements that are swung in a concentric radius with the acoustic membrane of the apparatus, instead of rotated, thereby removing any limitations on the size of the array of transducer elements.

It is yet another object of the present invention to provide a method and apparatus for performing ultrasound imaging for diagnostic procedures having a wet module coupled to a dry module which eliminates leakage from the wet module to the dry module, and thereby eliminates damage to the dry module resulting from such leakage.

Yet another object of the present invention is to provide a method and apparatus for diagnostic ultrasound imaging having a wet module comprising an array of ultrasound transducer elements in an oil or other suitable acoustic coupling liquid and means for driving the transducer elements, a dry module comprising the electronics to power the driving means, a fluid impervious seal separating the wet module from the dry module, and a flexible printed circuit board which traverses the seal and connects the electronics to the transducer array.

It is still a further object of the present invention to provide a method and apparatus for performing diagnostic ultrasound imaging where the ultrasound imaging apparatus comprises a wet module, a dry module and a reliable seal between the wet and dry modules thereby increasing performance of the apparatus and enhancing the image quality.

It is yet another object of the present invention to provide a method and apparatus for performing diagnostic ultrasound imaging where the same continuous distance is maintained between the ultrasound transducer array and the scanning membrane of the apparatus in order to decrease acoustic reverberations during imaging.

It is yet a further object of the present invention to provide a method and apparatus for performing ultrasound imaging for diagnostic procedures which removes limitations on the size of the transducer elements while controlling the size of the wet module containing the transducer elements to ensure that the resulting apparatus is small enough to be clinically useful.

It is still another object of the present invention to provide a method and apparatus for performing three-dimensional

diagnostic ultrasound imaging that utilizes a concave array of transducer elements that rotate, which as a result, requires a very small coupling area between the scanhead and the body or membrane in order to perform the imaging.

Yet another object of the present invention is to provide a method and apparatus for performing diagnostic ultrasound imaging which involves generating a succession of longitudinal scans which are stacked together to create a three-dimensional image.

In brief, a preferred embodiment the diagnostic ultrasound imaging apparatus of the present invention includes a swing shaft having a longitudinal axis, at least one ultrasound transducer element, but preferably an array of transducer elements connected to the swing shaft at a predetermined distance from its longitudinal axis, means for swinging the transducer array in a concentric radius about the longitudinal axis of the swing shaft, power means for operating the transducer array, and means for displaying the echos that are received from operating the transducer array. The apparatus preferably comprises a wet housing module and a dry housing module. The wet housing module includes the swing shaft, the ultrasound transducer array, and means for swinging the ultrasound transducer array, all of which are contained in a wet medium. The dry housing module includes the electronics for connecting the ultrasound array contained in the wet housing module to a power source and to means for displaying the echos that are received from operating the transducer array, such as computer hardware and software. The wet and dry housing modules are coupled to one another but separated by a fluid impervious seal to prevent the wet medium from leaking into the dry housing module thereby causing damage to the dry housing module. The preferred means for connecting the ultrasound transducer array contained in the wet housing module to the electronics contained in the dry housing module is in the form of a flexible printed circuit board which passes through the fluid impervious seal while still enabling the seal to remain fluid impervious. Although less reliable with respect to leakage, other means for connecting the ultrasound transducer to the electronics in the dry housing module, as described in the prior art, may also be used in the apparatus of the present invention. Finally, the ultrasound transducer array preferably comprises a one, one and one-half dimensional, or two dimensional array of ultrasound transducer elements. The array may be a phased array or a linear array with the transducer elements preferably being convex.

A second embodiment of the diagnostic ultrasound imaging apparatus of the present invention includes a first housing module having an ultrasound transducer contained in a wet medium and means for rotating the ultrasound transducer about a longitudinal axis contained therein, a second housing module having electronics for operating the ultrasound transducer and for receiving information from the ultrasound transducer contained therein where the first and second housing modules are coupled to one another but separated by a fluid impervious seal. The ultrasound transducer contained in the first housing module is connected to the electronics contained in the second housing module by a flexible printed circuit board which traverses the fluid impervious seal without breaking the fluid impervious seal that exists between the two housing modules. The transducer may comprise a phased array or linear array of ultrasound transducer elements with the transducer elements having a concave configuration.

According to a broad aspect of the present invention, there is provided a method for performing diagnostic ultrasound imaging which includes the steps of positioning an ultra-

sound transducer array at a predetermined distance from the longitudinal axis of the probe of an ultrasound imaging apparatus, rotating and operating the transducer array about the longitudinal axis of the probe such that the ultrasound transducer array is maintained in a concentric position with the acoustic membrane of the probe, and compiling the sequential scanning data obtained from the ultrasound transducer to create a three dimensional image. The ultrasound transducer array generates a series of sequential two-dimensional scans which are then processed with computer software to create a three-dimensional image of the object scanned.

The objectives, features and advantages of the method and apparatus for performing diagnostic ultrasound imaging of the present invention will become more apparent to those skilled in the art from the following more detailed description of the preferred embodiments of the invention made in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic of a partial top plan view of the apparatus for performing diagnostic ultrasound imaging of the present invention showing the wet housing module and the seal member that separates the wet housing module from the dry housing module of the apparatus.

FIG. 2 is a schematic of a partial top plan view of the apparatus for performing diagnostic ultrasound imaging of the present invention showing the wet housing module of the apparatus including the mechanical driver assembly for driving the ultrasound transducer array, and the seal member that separates the wet housing module from the dry housing module of the apparatus.

FIG. 3 is a cross-sectional view of the components contained in the wet housing module of the apparatus for performing diagnostic ultrasound imaging of the present invention taken along line 3—3 of FIG. 2.

FIG. 4 is a schematic top plan view of the apparatus for performing diagnostic ultrasound imaging of the present invention showing both the wet and dry housing modules of the apparatus and the components thereof.

FIGS. 5A, 5B and 5C are sequential schematics showing the swinging movement of the ultrasound transducer array of the apparatus for performing diagnostic ultrasound imaging of the present invention.

FIGS. 5D, 5E and 5F are sequential schematics showing the rotating movement of the ultrasound transducer array of prior art apparatus for performing diagnostic ultrasound imaging.

FIG. 6 is a schematic of a partial top plan view of the apparatus for performing diagnostic ultrasound imaging of the present invention showing the wet housing module, having a curved linear array ultrasound transducer, and the seal member that separates the wet housing module from the dry housing module of the apparatus.

FIG. 7 is a schematic of a partial top plan view of the apparatus for performing diagnostic ultrasound imaging of the present invention showing the wet housing module, having a concave linear array ultrasound transducer, and the seal member that separates the wet housing module from the dry housing module of the apparatus.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the figures, where like reference numbers refer to similar elements, FIG. 4 shows a top schematic

view of the diagnostic ultrasound imaging apparatus **10** of the present invention. The diagnostic ultrasound imaging apparatus **10** includes a first (or wet) housing module **12** and a second (or dry) housing module **14** which are coupled together but separated at their juncture by a fluid impervious seal **16**. The wet housing module **12** includes an ultrasound transducer array **18** which is connected to a swing (or drive) shaft **20** having a longitudinal axis. The swing shaft **20** is coupled to a motor **22** and motor reduction gear **24** which drives the swing shaft **20** to rotate. As can be later seen with reference to FIGS. **3** and **5-7**, the ultrasound transducer array **18** is coupled to the swing shaft **20** via one or more bar members such that the ultrasound transducer array **18** is positioned at a predetermined distance from the swing shaft **20**. Further, the wet housing module **12** is filled with an acoustic coupling liquid **26** such as jojoba bean oil or mineral oils.

The dry housing module **14** includes connectors **28** which are coupled via hard connect to a flexible printed circuit board **30**. The flexible printed circuit board **30** is also coupled via hard connect to the ultrasound transducer array **18**. The flexible printed circuit board **30** traverses the fluid impervious seal **16**. The flexible printed circuit board **30** is centered upon entering the wet housing module **12** and then bends around the motor **22** and motor reduction gear **24**, as well as the swing shaft **20**, and then hard connects with the ultrasound transducer array **18**. The connectors **28** are coupled to a cable assembly **32** which is in turn connected to an ultrasound scanner and motor controller (not shown). The ultrasound scanner and motor controller are used to operate the ultrasound transducer array **18** and to receive and process echo data obtained from operating the ultrasound transducer array **18**. This processing is performed by utilizing computer software which sequentially stacks up a succession of two-dimensional longitudinal scans of the body or tissue taken by the ultrasound transducer array **18** to create a three-dimensional image. The portion of the flexible printed circuit board **30** which traverses the fluid impervious seal **16** is sealed within the seal **16** using epoxy or some other type of comparable glue or sealant. Finally, it should be noted that the wet housing module **12** includes an acoustic membrane **34**, with which the ultrasound transducer array **18** is concentrically positioned when the ultrasound transducer array **18** is swinging about the longitudinal axis of the swing shaft **20**. This configuration ensures that the spacing between the acoustic membrane **34** and the ultrasound transducer array **18** remains constant throughout the imaging process.

The connectors **28** may be multiple contact header pins or sockets or alternatively solder pads for direct cable connection. The connectors may be either surface mounted or non-surface mounted. The cable assembly is coupled to connectors **28** through corresponding mating parts. This configuration of the cable assembly **32** and connectors **28** allows a user to easily disconnect the cable assembly for repair, replacement and maintenance. The motor **22** is preferably a miniature stepping motor such as the AM1524 gearhead motor manufactured by MicroMo Electronics.

FIG. **1** shows a top view of the wet housing module of the diagnostic ultrasound imaging apparatus of the present invention. As previously described, the fluid impervious seal **16** separates the wet housing module **12** from the dry housing module. The wet housing module **12** contains a swing or drive shaft **20** which is connected to the motor reduction gear **22**. The ultrasound transducer array **18** is connected to the swing or drive shaft **20** by one or more bar members (not shown) which are later shown with reference

to FIGS. **2, 3**, and **5-7**. The wet housing module **12** is filled with an acoustic coupling liquid **26** and the ultrasound transducer array **18** is positioned in very close proximity to the acoustic membrane **34** in order to decrease ghost images and increase spatial resolution.

FIGS. **2** and **3** are more detailed schematics of the mechanical driver design used in the wet housing module **12** of the diagnostic ultrasound imaging apparatus **10** of the present invention. More specifically, FIG. **2** shows a schematic of a partial top plan view of the apparatus **10** depicting the mechanical driver assembly **36** contained in the wet housing module **12**. The swing or drive shaft **20**, the motor **22**, and the motor gear reduction **24** all comprise part of the mechanical driver assembly **36**. FIG. **2** also depicts the sweep angle **38** of the ultrasound transducer array **18**. The advantages of the sweep angle **38** of the ultrasound transducer array **18** and the images produced therefrom will be further discussed with reference to FIGS. **5A** through **5F**.

FIG. **3** shows a cross-sectional view of the mechanical driver assembly **36** attached to the ultrasound transducer array **18** taken along line **3-3** of FIG. **2**. The mechanical driver assembly **36** includes the motor **22**, a precision gear head **40**, and swing or drive shaft **20** all contained within a frame **42**. The motor **22** is coupled to the precision gear head **40** which is in turn coupled to the motor reduction gear **24**. Further, the swing or drive shaft **20** is coupled to a shaft reduction gear **44** which interconnects with the motor reduction gear **24** so that the swing or drive shaft **20** can be driven by motor **22**. The ultrasound transducer array **18** is connected to the swing or drive shaft **20** by bar members **46** resulting in positioning of the ultrasound transducer array **18** at a predetermined distance from the swing or drive shaft **20**. The importance of positioning the ultrasound transducer array **18** at a predetermined distance from the axis of rotation of the swing or drive shaft **20** is later described in detail with reference to FIGS. **5A** through **5F**. Finally, a potentiometer assembly **48** is coupled to the swing or drive shaft **20** at the end of the swing or drive shaft **20** which is opposite the shaft reduction gear **44**. The potentiometer assembly **48**, or other position sensor, such as a Hall-effect switch and magnet, serves as a feedback element to help control the pointing direction of the transducer.

It is contemplated that the ultrasound transducer array **18** will comprise a one, one and one-half dimensional (1.5D) array, or two dimensional (2D) array. A 2D phased array has a large number of elements in both the azimuth and elevation dimensions. Therefore, 2D arrays can focus and steer the acoustic beam in both dimensions. As a result, a 2D array can scan a pyramidal region in real time to produce a volumetric image using parallel received processing. The 1.5D array is similar to a 2D array in construction but a 1D array in operation. Like the 2D array, the 1.5D array contains elements along both the azimuth and elevation dimensions. With the 1.5D array, dynamic focusing and phase correction can be implemented in both dimensions to improve image quality. However, since a 1.5D array contains a limited number of elements in elevation, steering is not possible in that direction. Linear sequential scanning is also possible with 1.5D arrays.

In using a 1.5D array for linear sequential scanning, the ultrasound imaging apparatus **10** of the present invention creates a sequential series of 2-dimensional slices which are stacked together to create a 3-dimensional image. In contrast, a 2D phased array can scan a pyramidal region in real time to produce a 3-dimensional image.

Turning now to FIG. **5**, FIGS. **5A** through **5C** are sequential schematics showing the swinging movement of the

ultrasound transducer array **18** of the apparatus **10** for performing diagnostic ultrasound imaging of the present invention. In contrast, FIGS. **5D** through **5F** are sequential schematics showing the rotating movement of the ultrasound transducer array of prior art apparatus for performing diagnostic ultrasound imaging. More particularly, FIGS. **5D** through **5F** show a rotating transducer module **50** which rotates about an axis **52** located in the middle of the transducer module **50**. As the transducer module **50** rotates in a counter-clockwise direction, the transducer module **50** touches the acoustic membrane **34**, then moves to a position where the transducer module **50** is separated from the acoustic membrane by a constant length, and then moves away from the acoustic membrane **34**, which results in the transducer module **50** being at a distance away from the acoustic membrane **34** that is six times the distance between the transducer module **50** and acoustic membrane **34** in FIG. **5E**. In order to avoid hitting the acoustic membrane **34**, one can reduce the size of the transducer module **50** in an effort to move the transducer module **50** away from the acoustic membrane **34**. However, reducing the size of the transducer module **50** would prevent the use of a 1.5D array because elevation dimension would be restricted which in turn would limit the focusing ability of the transducer in that dimension. Also, as the transducer module **50** moves farther from the acoustic membrane **34**, the acoustic coupling liquid absorbs more of the acoustic beam because of the larger distance between the acoustic membrane **34** and the transducer module **50**. Further, the physical size of the wet housing module **12** would need to be larger and ultimately could be too large to be clinically useful. Finally, acoustic reverberations exist between the transducer module **50** and the acoustic membrane **34** which decrease resolution by creating ghost images.

In contrast to FIGS. **5D** through **5F**, FIGS. **5A** through **5C** depict a transducer module **50** which rotates about a longitudinal axis **54** of a swing shaft **20** at a predetermined distance **56** from the swing shaft **20**. This configuration results in a transducer module **50** which swings in a concentrically constant position with the acoustic membrane **34**. Accordingly, the distance between the transducer module **50** and the acoustic membrane **34** in each of FIGS. **5A**, **5B** and **5C** is constant throughout the imaging process. As a result, there are no longer any limitations on the size of the array of transducer elements. Therefore, a 1.5D or 2D transducer array may be used which means that the array can be focused in the elevation dimension in order to provide more flexibility and better shape of the focal region. This also results in a decrease in acoustic reverberations and an increase in resolution of the image.

A schematic of a partial top plan view of the apparatus for performing diagnostic ultrasound imaging of the present invention having a convex linear transducer array is shown in FIG. **6**. The wet housing module **12** is coupled to the fluid impervious seal **16**. The wet housing module **12** contains the mechanical driver assembly **36**, the drive shaft **70**, which is connected to the mechanical driver assembly **36**, and the convex transducer array **18** which is connected to the drive shaft **70**. The wet housing member **12** is filled with an acoustic coupling liquid **26** and also comprises the acoustic membrane **34** which is the membrane of the apparatus **10** that is used to scan the patient. The method for performing ultrasound imaging with this type of wet housing module configuration involves rotating the convex transducer array

18 about the acoustic membrane **34** by rotating the drive shaft **70** which is driven by the mechanical driver assembly **36**.

Another embodiment of the ultrasound imaging apparatus of the present invention showing a schematic of a partial top plan view of the apparatus having a concave linear transducer array is illustrated in FIG. **7**. Again, as in FIG. **6**, the wet housing module **12** is coupled to the fluid impervious seal **16** which separates the wet housing module **12** from the dry housing module (not shown). The wet housing module **12** contains the mechanical driver assembly **36**, the drive shaft **70**, which is driven by the mechanical driver assembly **36**, and the concave linear transducer array **58** which is connected to the drive shaft **70**. The wet housing module is filled with an acoustic coupling fluid **26**. Further, as previously described in FIG. **6**, the concave linear array **58** is directly coupled to the drive shaft **70** and thereby rotates about its own center longitudinal axis when in use. In utilizing a concave linear transducer array **58**, the beams from each ultrasound transducer element pass through the acoustic membrane **34** and converge at a set point **60**. This type of concave transducer configuration is particularly useful in those applications where ultrasound imaging needs to be performed in a small confined area, such as the heart, where it is necessary to avoid hitting the lungs and ribs with ultrasound beams.

While preferred forms of the invention have been shown in the drawings and described, since variations in the preferred forms will be apparent to those skilled in the art, the invention should not be construed as limited to the specific form shown and described, but instead is as set forth in the following claims.

We claim:

1. An apparatus for ultrasound imaging comprising:

- (a) at least one of a swinging or rotating multiple element transducer array;
- (b) means for electrically connecting said multiple element transducer array to a coaxial cable assembly;
- (c) drive means for swinging said swinging multiple element transducer array about a 90 degree angle or for rotating said rotating multiple element transducer array about a 180 degree angle;
- (d) means for transmitting and receiving a plurality of electrical signals from said multiple element transducer array through said means for electrically connecting said multiple element transducer array; and
- (e) means for processing and displaying said plurality electrical signals into an ultrasound image.

2. The apparatus of claim 1 wherein said means for electrically connecting said multiple element transducer array to a coaxial cable assembly comprises a flexible printed circuit board and at least one connector element.

3. The apparatus of claim 1 wherein said means for electrically connecting said multiple element transducer array to a coaxial cable assembly comprises at least one flexible conductor cable connected to at least one hermetically sealed pin connector which is in turn connected to said coaxial cable assembly.

4. The apparatus of claim 1 further comprising a wet housing module which contains said multiple element transducer array and said drive means.

5. The apparatus of claim 4 wherein said wet housing module is filled with an acoustic coupling liquid such that said multiple element transducer and said drive means are immersed in said acoustic coupling liquid.

6. The apparatus of claim 5 further comprising a dry housing module connected to said wet housing module and

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a fluid impervious seal separating said wet module from said dry module.

7. The apparatus of claim 1 wherein said at least one multiple element transducer comprises a linear array of a plurality of transducer elements.

8. The apparatus of claim 7 wherein said linear array is a phased array.

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9. The apparatus of claim 1 wherein said at least one multiple element transducer array comprises at least one of a one dimensional transducer array, a one and one-half dimensional transducer array, or a two dimensional transducer array.

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